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(54) **BALLOON POWER SOURCES WITH A BUOYANCY TRADE-OFF**

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Related U.S. Application Data

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G05D 1/04	(2006.01)
B64B 1/40	(2006.01)
H02S 20/30	(2014.01)
C25B 1/04	(2006.01)

(52) **U.S. Cl.**
CPC ***G05D 1/042*** (2013.01); ***B64B 1/40*** (2013.01); ***B64B 1/62*** (2013.01); ***C25B 1/04*** (2013.01); ***H02S 20/30*** (2014.12)

(58) **Field of Classification Search**
CPC B64B 1/44; B64B 1/58; B64B 1/62
See application file for complete search history.

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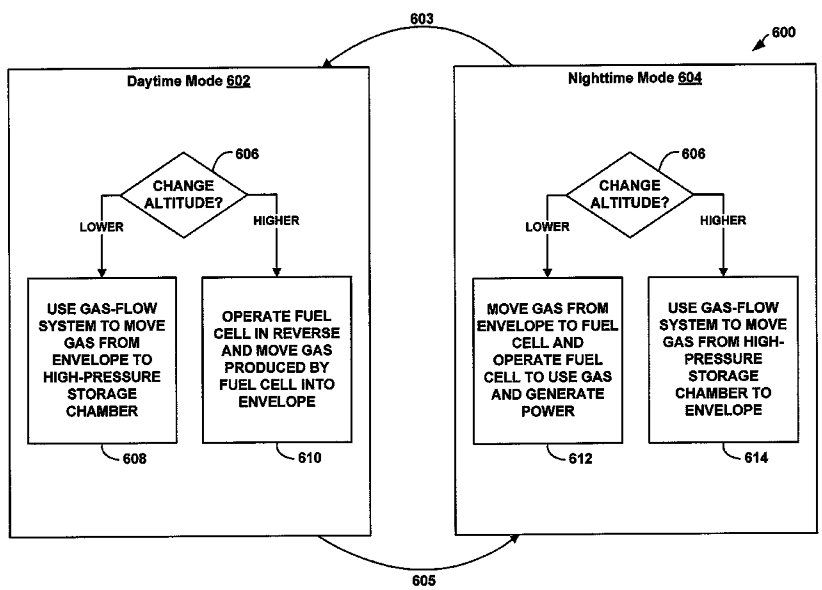
(57) **ABSTRACT**

Example embodiments may facilitate altitude control by a balloon in a balloon network. An example method involves: (a) causing a balloon to operate in a first mode, wherein the balloon comprises an envelope, a high-pressure storage chamber, and a solar power system, (b) while the balloon is operating in the first mode: (i) operating the solar power system to generate power for the balloon and (ii) using at least some of the power generated by the solar power system to move gas from the envelope to the high-pressure storage chamber such that the buoyancy of the balloon decreases; (c) causing the balloon to operate in a second mode; and while the balloon is operating in the second mode, moving gas from the high-pressure storage chamber to the envelope such that the buoyancy of the balloon increases.

20 Claims, 6 Drawing Sheets



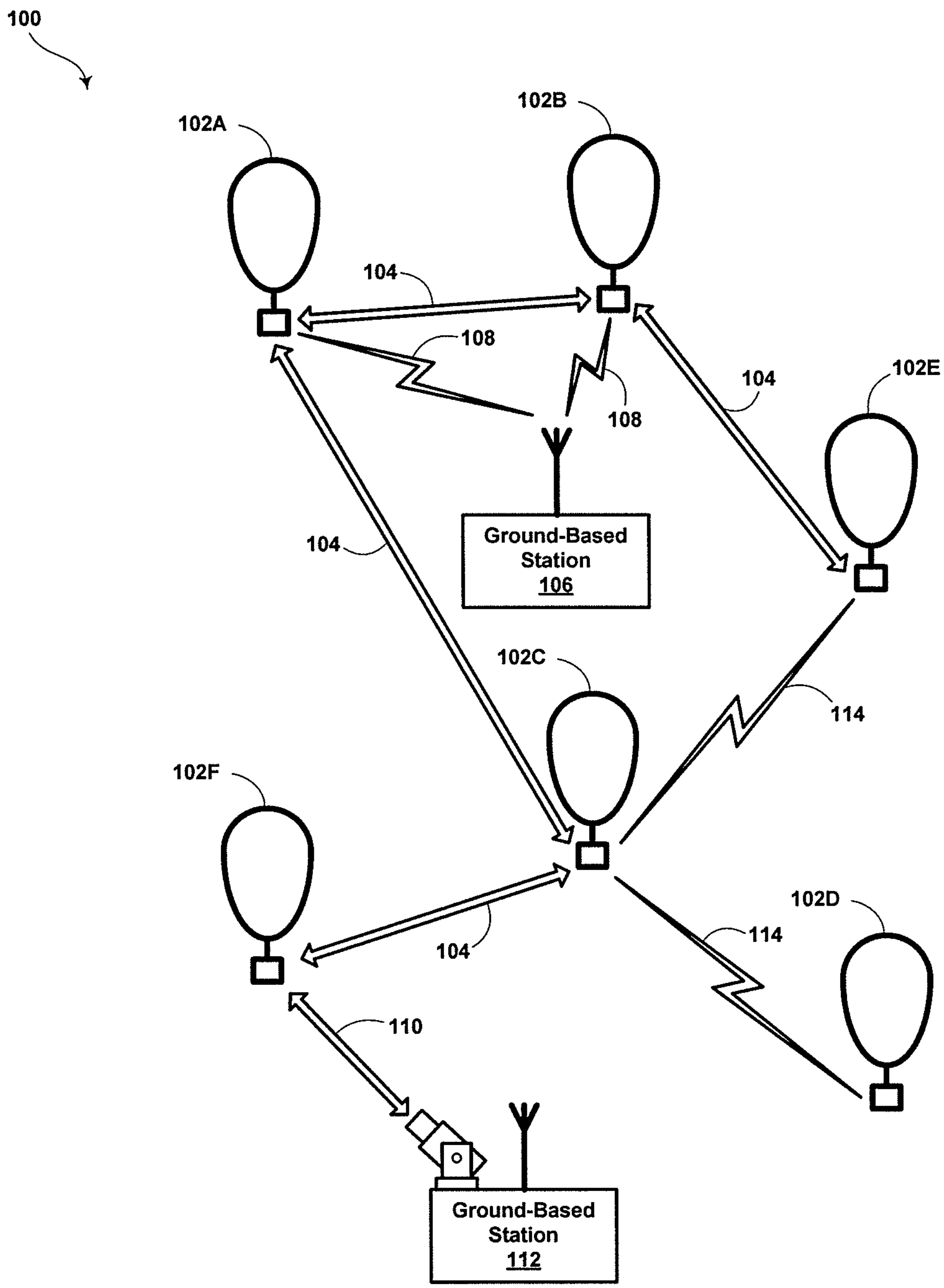
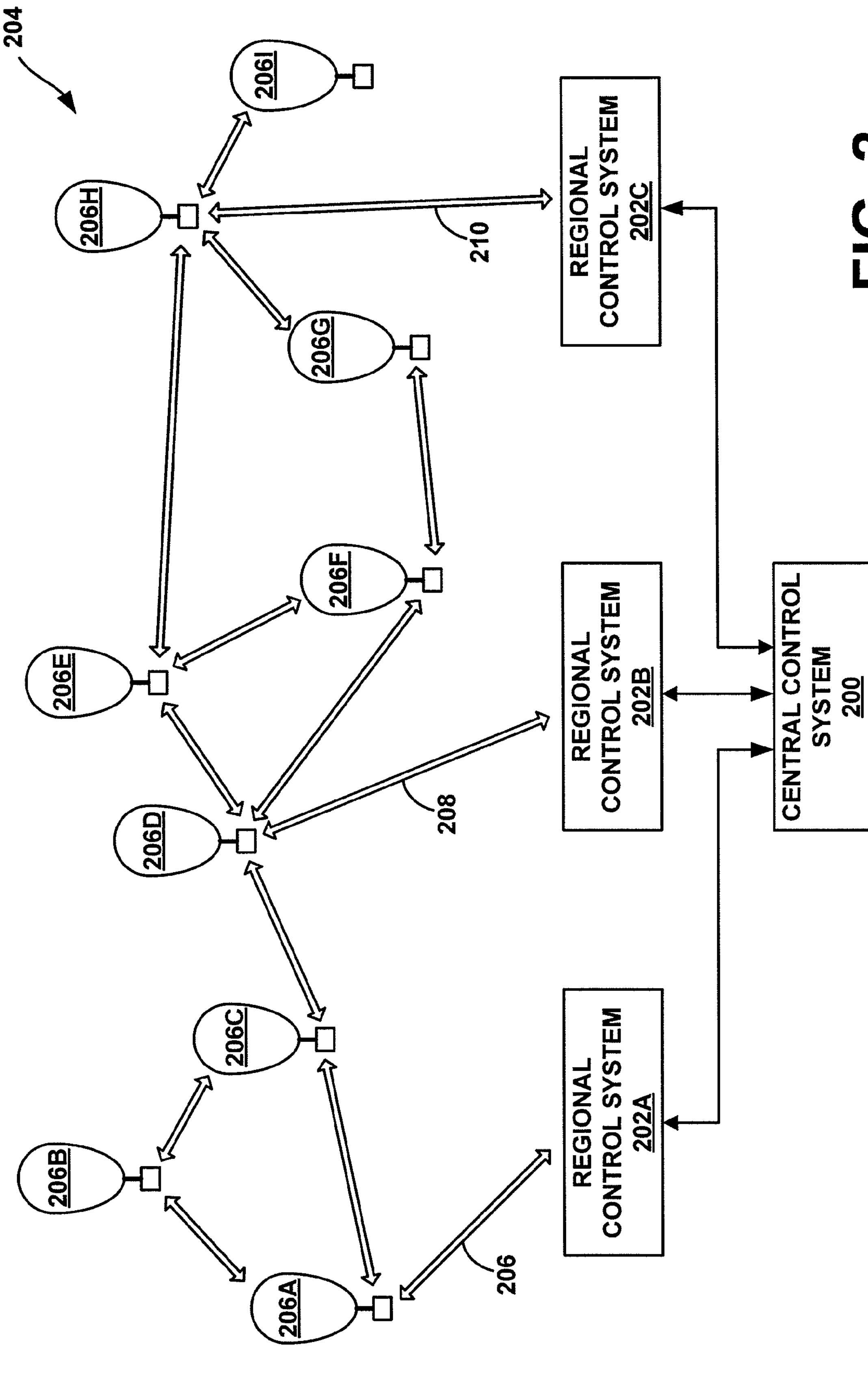
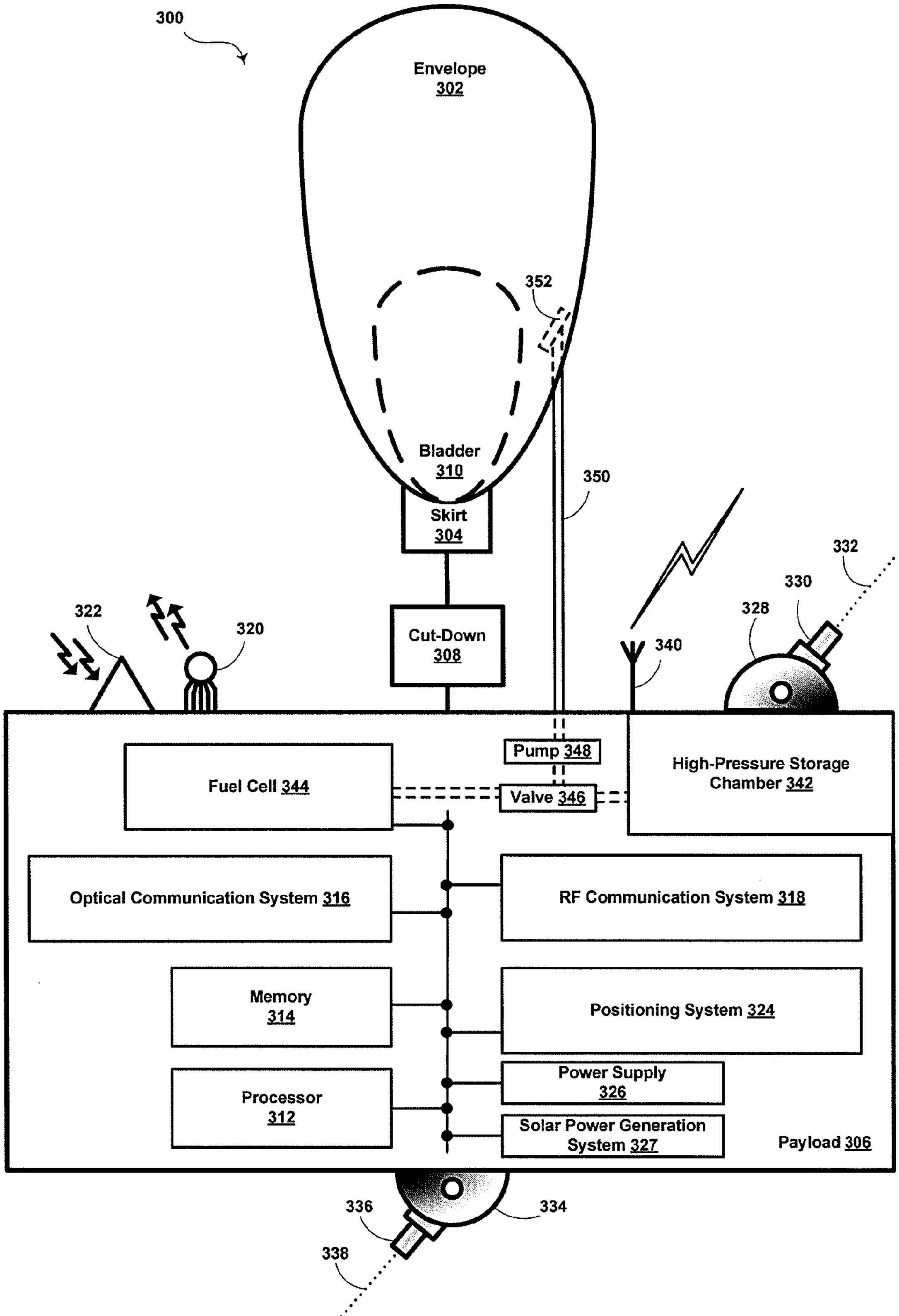

100
102A
102B
104
108
108
104
102E
104
Ground-Based
Station
106
102C
114
102F
102D
114
104
110
Ground-Based
Station
112

Figure 1



204
206I
206H
206G
206F
206E
206D
206C
206B
206A
210
208
206
REGIONAL CONTROL SYSTEM 202C
REGIONAL CONTROL SYSTEM 202B
REGIONAL CONTROL SYSTEM 202A
CENTRAL CONTROL SYSTEM 200

FIG. 2



300
Envelope
302
352
Bladder
310
350
Skirt
304
332
330
328
Cut-Down
308
322
320
340
Pump 348
High-Pressure Storage
Chamber 342
Fuel Cell 344
Valve 346
Optical Communication System 316
RF Communication System 318
Memory
314
Positioning System 324
Power Supply
326
Processor
312
Solar Power Generation
System 327
Payload 306
336
334
338

Figure 3

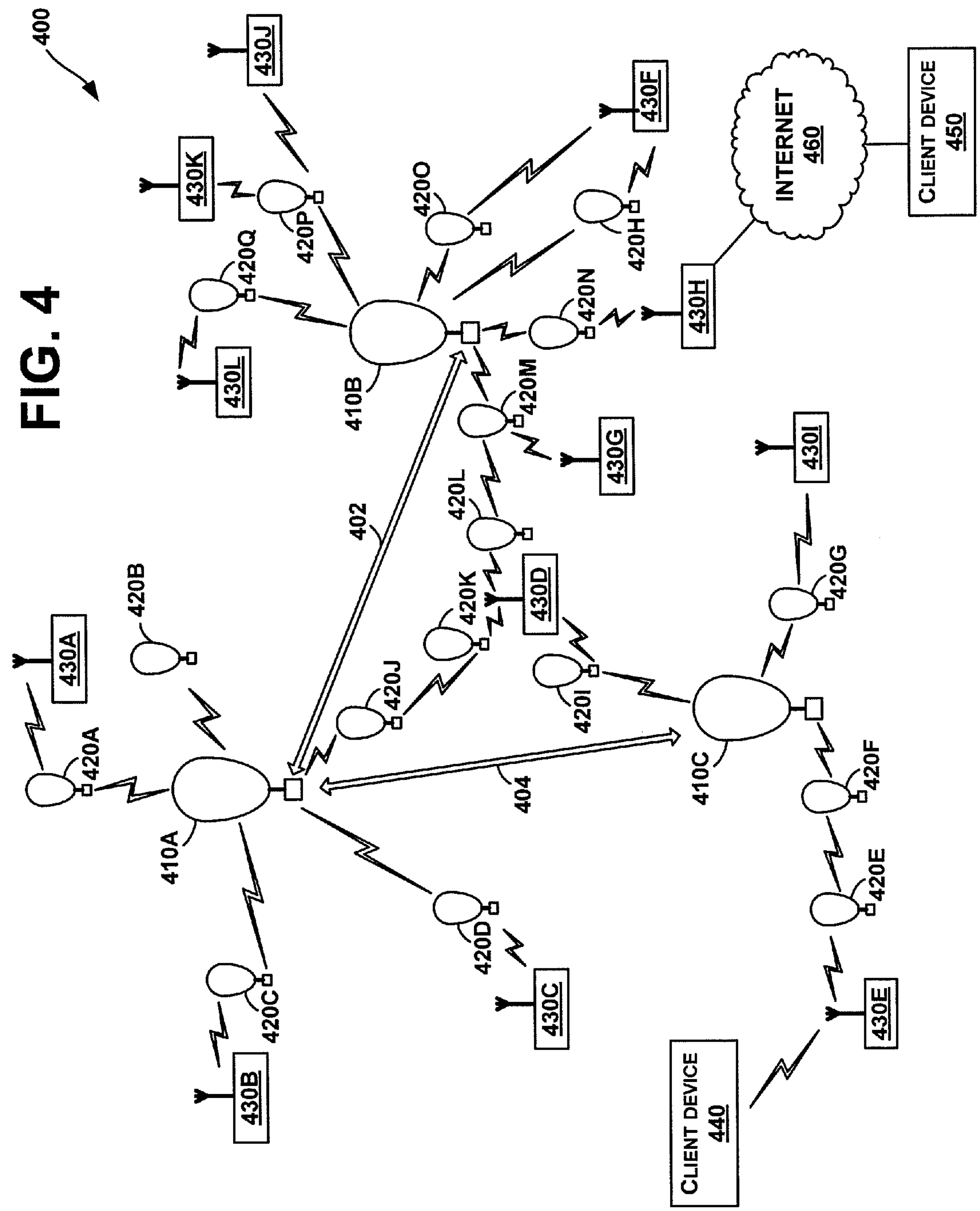

400
430J
430K
430F
420P
420O
420Q
420H
INTERNET
460
CLIENT DEVICE
450
430L
410B
420N
430H
420M
430G
430I
402
420L
420B
430A
420K
430D
420G
420J
420I
420A
410C
404
420F
410A
420E
420D
420C
430C
430E
430B
CLIENT DEVICE
440

FIG. 4

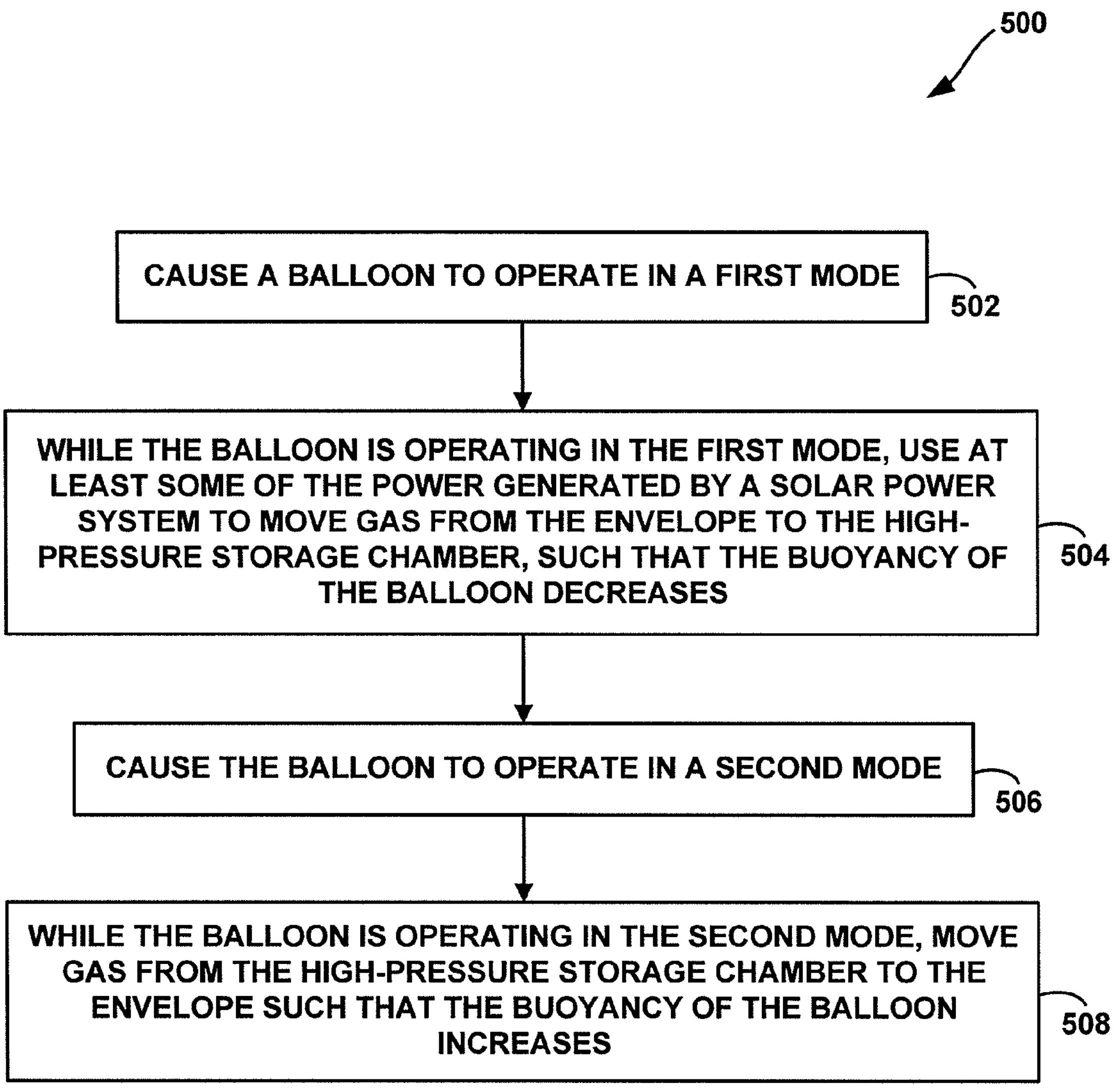

500
CAUSE A BALLOON TO OPERATE IN A FIRST MODE
502
WHILE THE BALLOON IS OPERATING IN THE FIRST MODE, USE AT LEAST SOME OF THE POWER GENERATED BY A SOLAR POWER SYSTEM TO MOVE GAS FROM THE ENVELOPE TO THE HIGH-PRESSURE STORAGE CHAMBER, SUCH THAT THE BUOYANCY OF THE BALLOON DECREASES
504
CAUSE THE BALLOON TO OPERATE IN A SECOND MODE
506
WHILE THE BALLOON IS OPERATING IN THE SECOND MODE, MOVE GAS FROM THE HIGH-PRESSURE STORAGE CHAMBER TO THE ENVELOPE SUCH THAT THE BUOYANCY OF THE BALLOON INCREASES
508

FIG. 5

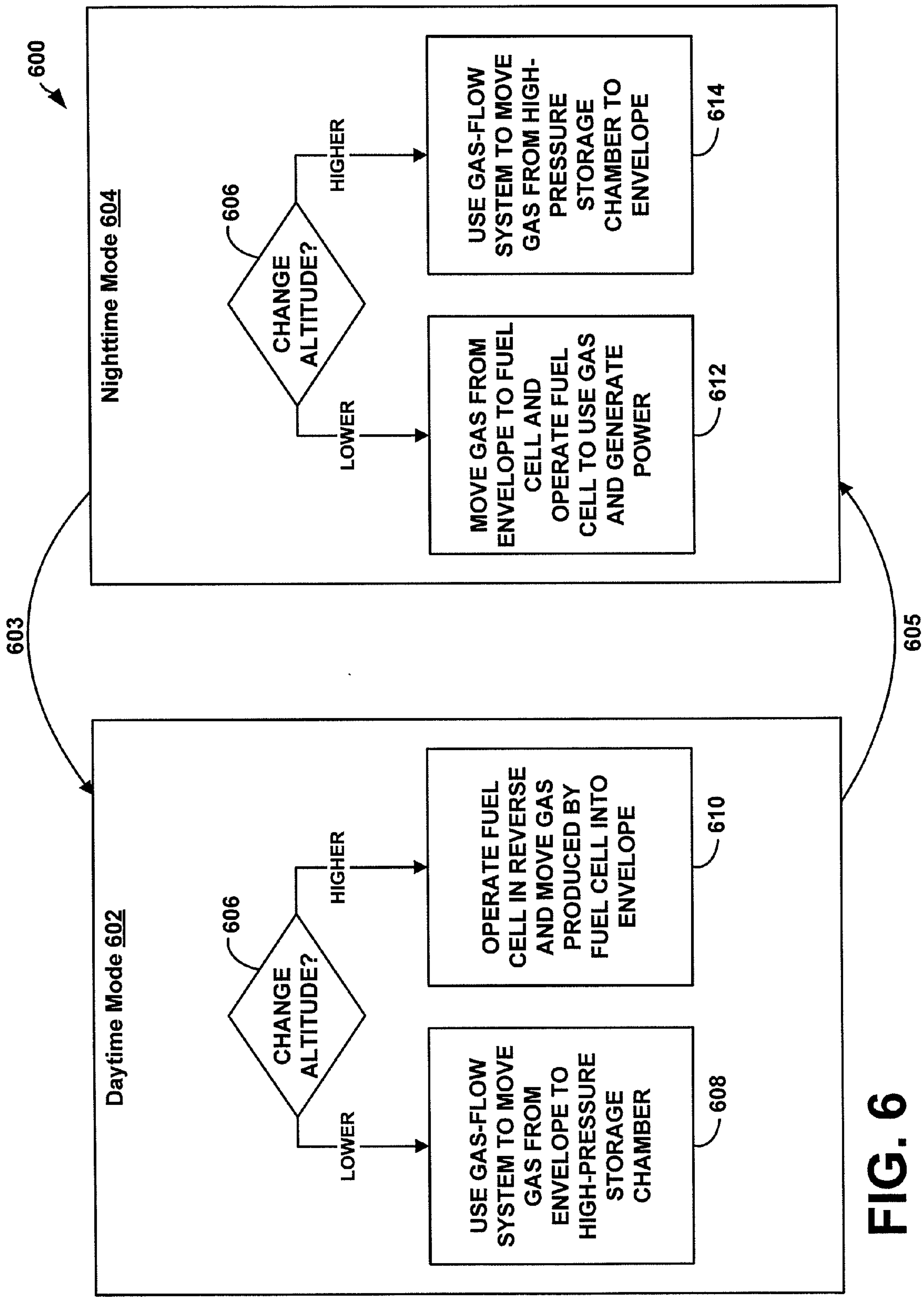

600
Nighttime Mode 604
606
CHANGE ALTITUDE?
LOWER
HIGHER
MOVE GAS FROM ENVELOPE TO FUEL CELL AND OPERATE FUEL CELL TO USE GAS AND GENERATE POWER
612
USE GAS-FLOW SYSTEM TO MOVE GAS FROM HIGH-PRESSURE STORAGE CHAMBER TO ENVELOPE
614
603
605
Daytime Mode 602
606
CHANGE ALTITUDE?
LOWER
HIGHER
USE GAS-FLOW SYSTEM TO MOVE GAS FROM ENVELOPE TO HIGH-PRESSURE STORAGE CHAMBER
608
OPERATE FUEL CELL IN REVERSE AND MOVE GAS PRODUCED BY FUEL CELL INTO ENVELOPE
610

FIG. 6

BALLOON POWER SOURCES WITH A BUOYANCY TRADE-OFF

CROSS REFERENCE TO RELATED APPLICATIONS

This application claims is a continuation of U.S. patent application Ser. No. 13/590,020, filed Aug. 20, 2012, entitled "Balloon Power Sources with a Buoyancy Trade-Off", now pending, the contents of which are incorporated by reference herein for all purposes.

BACKGROUND

Unless otherwise indicated herein, the materials described in this section are not prior art to the claims in this application and are not admitted to be prior art by inclusion in this section.

Computing devices such as personal computers, laptop computers, tablet computers, cellular phones, and countless types of Internet-capable devices are increasingly prevalent in numerous aspects of modern life. As such, the demand for data connectivity via the Internet, cellular data networks, and other such networks, is growing. However, there are many areas of the world where data connectivity is still unavailable, or if available, is unreliable and/or costly. Accordingly, additional network infrastructure is desirable.

SUMMARY

In one aspect, a computer-implemented method involves: (i) causing a balloon to operate in a first mode, wherein the balloon comprises an envelope, a high-pressure storage chamber, and a solar power system; (ii) while the balloon is operating in the first mode: (a) operating the solar power system to generate power for the balloon and (b) using at least some of the power generated by the solar power system to move gas from the envelope to the high-pressure storage chamber such that the buoyancy of the balloon decreases; (iii) causing the balloon to operate in a second mode; and (iv) while the balloon is operating in the second mode, moving gas from the high-pressure storage chamber to the envelope such that the buoyancy of the balloon increases.

In another aspect, a non-transitory computer readable medium may have stored therein instructions that are executable by a computing device to cause the computing device to perform functions including: (i) causing a balloon to operate in a first mode, wherein the balloon comprises an envelope, a high-pressure storage chamber, and a solar power system; (ii) while the balloon is operating in the first mode: (a) operating the solar power system to generate power for the balloon; and (b) using at least some of the power generated by the solar power system to move gas from the envelope to the high-pressure storage chamber such that the buoyancy of the balloon decreases; (iii) causing the balloon to operate in a second mode; and (iv) while the balloon is operating in the second mode, moving gas from the high-pressure storage chamber to the envelope such that the buoyancy of the balloon increases.

In a further aspect, a balloon includes: (i) a solar power system configured to generate power for a balloon, wherein the balloon comprises an envelope and a high-pressure storage chamber; and (ii) a control system that is configured to: (a) decrease buoyancy of the balloon via use of power generated by the solar power system to move gas from the envelope to the high-pressure storage chamber, wherein movement of gas from the envelope to the high-pressure storage chamber reduces a volume in which the moved gas is contained; and (b) increase the buoyancy of the balloon via movement of gas from the high-pressure storage chamber to the envelope.

In yet a further aspect, a computer implemented method may involve: (a) causing a balloon to operate in a first mode, wherein the balloon comprises an envelope, a high-pressure storage chamber, and a solar power system; (b) while the balloon is operating in the first mode: (i) operating the solar power system to generate power for the balloon; and (ii) using at least some of the power generated by the solar power system to move gas from the envelope to the high-pressure storage chamber; (c) causing the balloon to operate in a second mode; and (d) while the balloon is operating in the second mode, moving gas from the high-pressure storage chamber to the envelope

These as well as other aspects, advantages, and alternatives, will become apparent to those of ordinary skill in the art by reading the following detailed description, with reference where appropriate to the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a simplified block diagram illustrating a balloon network, according to an example embodiment.

FIG. **2** is a block diagram illustrating a balloon-network control system, according to an example embodiment.

FIG. **3** is a simplified block diagram illustrating a high-altitude balloon, according to an example embodiment.

FIG. **4** is a simplified block diagram illustrating a balloon network that includes super-nodes and sub-nodes, according to an example embodiment.

FIG. **5** is a flow chart illustrating a computer-implemented method, according to an example embodiment.

FIG. **6** is a combined operational state diagram illustrating the functions of a balloon that utilizes a fuel cell and a gas-flow system for altitude control, according to an example embodiment.

DETAILED DESCRIPTION

Example methods and systems are described herein. Any example embodiment or feature described herein is not necessarily to be construed as preferred or advantageous over other embodiments or features. The example embodiments described herein are not meant to be limiting. It will be readily understood that certain aspects of the disclosed systems and methods can be arranged and combined in a wide variety of different configurations, all of which are contemplated herein.

Furthermore, the particular arrangements shown in the Figures should not be viewed as limiting. It should be understood that other embodiments may include more or less of each element shown in a given Figure. Further, some of the illustrated elements may be combined or omitted. Yet further, an example embodiment may include elements that are not illustrated in the Figures.

1. Overview

Example embodiments may be implemented in the context of a data network that includes a plurality of balloons; for example, a mesh network formed by high-altitude balloons deployed in the stratosphere. Since winds in the stratosphere may affect the locations of the balloons in a differential manner, each balloon in an example network may be configured to change its horizontal position by adjusting its vertical position (i.e., altitude). For instance, by adjusting its altitude, a balloon may be able find winds that will carry it horizontally (e.g., latitudinally and/or longitudinally) to a desired horizontal location.

To function as a node in a balloon network, a balloon may consume a significant amount of power. However, increasing the amount of power supplied by a battery (e.g., a Lithium-ion battery) and/or the increasing the number of batteries on a balloon will typically increase the size and weight of the battery or batteries, which may be undesirable for various reasons. Accordingly, an exemplary embodiment may include one or more altitude control mechanisms that also function as supplemental power systems, and generate power as part of the processes to increase or decrease the altitude of the balloon.

In an example embodiment, a balloon may move gas (e.g., hydrogen or another lighter-than-air gas) between its envelope and a high-pressure storage chamber to decrease or increase its buoyancy. More specifically, the high-pressure storage chamber may be sized and configured such that the density of gas increases when the gas is moved from the envelope to the high-pressure storage chamber. As such, the balloon may pump gas out of the envelope and into the high-pressure storage chamber to decrease its buoyancy. Conversely, the balloon may move gas back into the envelope from the high-pressure storage chamber to increase its buoyancy. This gas flow can be used as a source of power at night, and it increases buoyancy.

Altitude control via movement of gas between the high-pressure storage chamber and the envelope (referred to herein as a "gas-flow" altitude control mechanism) may be configured so as to consume power during the day, when solar power is plentiful, and to generate power via altitude control during the night. In particular, during the day, the balloon may use the gas-flow system for some or all altitudinal decreases, and use other altitude control techniques for some or all altitudinal increases. As such, gas may be stored in the high-pressure storage chamber during the day. Then, during the night, the balloon may use the gas-flow system for some or all altitudinal increases, and use another technique for some or all altitudinal decreases. Thus, use of the gas-flow system may consume power during the day when solar power is more-readily available, and generate power during the night, when solar power is less usable.

In some embodiments, a balloon may also use a fuel cell for altitude control. Fuel cells can produce power via the chemical reaction of hydrogen and oxygen to produce water. Further, fuel cells can also be run in reverse to create hydrogen and oxygen from water. Accordingly, to increase its altitude, a balloon may run its fuel cell in reverse so as to generate gas (e.g., hydrogen gas), which can then be moved into the envelope to increase buoyancy. Further, to decrease its altitude, a fuel cell may be configured to use gas from the envelope to generate power (e.g., via the chemical reaction of hydrogen from the envelope and oxygen to produce water).

In a further aspect, a balloon may implement an altitude control process that uses a fuel cell and a gas-flow system. Specifically, during the day, the balloon may use the gas-flow system to decrease its altitude, and operate a fuel cell in reverse to increase its altitude. Both these altitude-control techniques may consume power, but doing so during the day when more solar power is available. Further, the combination of these process creates and stores gas (e.g., hydrogen gas), which is then available for consumption during the night. In particular, during the night, the balloon may use the gas-flow system to increase its altitude, and operate the fuel cell to decrease its altitude. Thus, during the night, the mechanisms for increasing and decreasing the balloon's altitude may both generate power, which may be immediately used to operate the balloon and/or may be used to recharge the balloon's battery.

2. Example Balloon Networks

In an example balloon network, the balloons may communicate with one another using free-space optical communications. For instance, the balloons may be configured for optical communications using ultra-bright LEDs (which are also referred to as "high-power" or "high-output" LEDs). In some instances, lasers could be used instead of or in addition to LEDs, although regulations for laser communications may restrict laser usage. In addition, the balloons may communicate with ground-based station(s) using radio-frequency (RF) communications.

In some embodiments, a high-altitude-balloon network may be homogenous. That is, the balloons in a high-altitude-balloon network could be substantially similar to each other in one or more ways. More specifically, in a homogenous high-altitude-balloon network, each balloon is configured to communicate with nearby balloons via free-space optical links. Further, some or all of the balloons in such a network, may also be configured communicate with ground-based station(s) using RF communications. (Note that in some embodiments, the balloons may be homogenous in so far as each balloon is configured for free-space optical communication with other balloons, but heterogeneous with regard to RF communications with ground-based stations.)

In other embodiments, a high-altitude-balloon network may be heterogeneous, and thus may include two or more different types of balloons. For example, some balloons may be configured as super-nodes, while other balloons may be configured as sub-nodes. Some balloons may be configured to function as both a super-node and a sub-node. Such balloons may function as either a super-node or a sub-node at a particular time, or, alternatively, act as both simultaneously depending on the context. For instance, an example balloon could aggregate search requests of a first type to transmit to a ground-based station. The example balloon could also send search requests of a second type to another balloon, which could act as a super-node in that context.

In such a configuration, the super-node balloons may be configured to communicate with nearby super-node balloons via free-space optical links. However, the sub-node balloons may not be configured for free-space optical communication, and may instead be configured for some other type of communication, such as RF communications. In that case, a super-node may be further configured to communicate with sub-nodes using RF communications. Thus, the sub-nodes may relay communications between the super-nodes and one or more ground-based stations using RF communications. In this way, the super-nodes may collectively function as backhaul for the balloon network, while the sub-nodes function to relay communications from the super-nodes to ground-based stations. Other differences could be present between balloons in a heterogeneous balloon network.

FIG. **1** is a simplified block diagram illustrating a balloon network **100**, according to an example embodiment. As shown, balloon network **100** includes balloons **102**A to **102**F, which are configured to communicate with one another via free-space optical links **104**. Balloons **102**A to **102**F could additionally or alternatively be configured to communicate with one another via RF links **114**. Balloons **102**A to **102**F may collectively function as a mesh network for packet-data communications. Further, balloons **102**A to **102**F may be configured for RF communications with ground-based stations **106** and **112** via RF links **108**. In another example embodiment, balloons **102**A to **102**F could be configured to communicate via optical link **110** with ground-based station **112**.

In an example embodiment, balloons **102**A to **102**F are high-altitude balloons, which are deployed in the stratosphere. At moderate latitudes, the stratosphere includes altitudes between approximately 10 kilometers (km) and 50 km altitude above the surface. At the poles, the stratosphere starts at an altitude of approximately 8 km. In an example embodiment, high-altitude balloons may be generally configured to operate in an altitude range within the stratosphere that has lower winds (e.g., between 5 and 20 miles per hour (mph)).

More specifically, in a high-altitude-balloon network, balloons **102**A to **102**F may generally be configured to operate at altitudes between 17 km and 25 km (although other altitudes are possible). This altitude range may be advantageous for several reasons. In particular, this layer of the stratosphere generally has mild wind and turbulence (e.g., winds between 5 and 20 miles per hour (mph)). Further, while the winds between 17 km and 25 km may vary with latitude and by season, the variations can be modelled in a reasonably accurate manner. Additionally, altitudes above 17 km are typically above the maximum flight level designated for commercial air traffic. Therefore, interference with commercial flights is not a concern when balloons are deployed between 17 km and 25 km.

To transmit data to another balloon, a given balloon **102**A to **102**F may be configured to transmit an optical signal via an optical link **104**. In an example embodiment, a given balloon **102**A to **102**F may use one or more high-power light-emitting diodes (LEDs) to transmit an optical signal. Alternatively, some or all of balloons **102**A to **102**F may include laser systems for free-space optical communications over optical links **104**. Other types of free-space optical communication are possible. Further, in order to receive an optical signal from another balloon via an optical link **104**, a given balloon **102**A to **102**F may include one or more optical receivers. Additional details of example balloons are discussed in greater detail below, with reference to FIG. **3**.

In a further aspect, balloons **102**A to **102**F may utilize one or more of various different RF air-interface protocols for communication ground-based stations **106** and **112** via RF links **108**. For instance, some or all of balloons **102**A to **102**F may be configured to communicate with ground-based stations **106** and **112** using protocols described in IEEE 802.11 (including any of the IEEE 802.11 revisions), various cellular protocols such as GSM, CDMA, UMTS, EV-DO, WiMAX, and/or LTE, and/or one or more propriety protocols developed for balloon-to-ground RF communication, among other possibilities.

In a further aspect, there may scenarios where RF links **108** do not provide a desired link capacity for balloon-to-ground communications. For instance, increased capacity may be desirable to provide backhaul links from a ground-based gateway, and in other scenarios as well. Accordingly, an example network may also include downlink balloons, which could provide a high-capacity air-ground link.

For example, in balloon network **100**, balloon **102**F could be configured as a downlink balloon. Like other balloons in an example network, a downlink balloon **102**F may be operable for optical communication with other balloons via optical links **104**. However, downlink balloon **102**F may also be configured for free-space optical communication with a ground-based station **112** via an optical link **110**. Optical link **110** may therefore serve as a high-capacity link (as compared to an RF link **108**) between the balloon network **100** and a ground-based station **112**.

Note that in some implementations, a downlink balloon **102**F may additionally be operable for RF communication with ground-based stations **106**. In other cases, a downlink balloon **102**F may only use an optical link for balloon-to-ground communications. Further, while the arrangement shown in FIG. **1** includes just one downlink balloon **102**F, an example balloon network can also include multiple downlink balloons. On the other hand, a balloon network can also be implemented without any downlink balloons.

In other implementations, a downlink balloon may be equipped with a specialized, high-bandwidth RF communication system for balloon-to-ground communications, instead of, or in addition to, a free-space optical communication system. The high-bandwidth RF communication system may take the form of an ultra-wideband system, which provides an RF link with substantially the same capacity as the optical links **104**. Other forms are also possible.

Balloons could be configured to establish a communication link with space-based satellites in addition to, or as an alternative to, a ground-based communication link.

Ground-based stations, such as ground-based stations **106** and/or **112**, may take various forms. Generally, a ground-based station may include components such as transceivers, transmitters, and/or receivers for communication via RF links and/or optical links with a balloon network. Further, a ground-based station may use various air-interface protocols in order communicate with a balloon **102**A to **102**F over an RF link **108**. As such, ground-based stations **106** and **112** may be configured as an access point with which various devices can connect to balloon network **100**. Ground-based stations **106** and **112** may have other configurations and/or serve other purposes without departing from the scope of the invention.

Further, some ground-based stations, such as ground-based stations **106** and **112**, may be configured as gateways between balloon network **100** and one or more other networks. Such ground-based stations **106** and **112** may thus serve as an interface between the balloon network and the Internet, a cellular service provider's network, and/or other types of networks. Variations on this configuration and other configurations of ground-based stations **106** and **112** are also possible.

2a) Mesh Network Functionality

As noted, balloons **102**A to **102**F may collectively function as a mesh network. More specifically, since balloons **102**A to **102**F may communicate with one another using free-space optical links, the balloons may collectively function as a free-space optical mesh network.

In a mesh-network configuration, each balloon **102**A to **102**F may function as a node of the mesh network, which is operable to receive data directed to it and to route data to other balloons. As such, data may be routed from a source balloon to a destination balloon by determining an appropriate sequence of optical links between the source balloon and the destination balloon. These optical links may be collectively referred to as a "lightpath" for the connection between the source and destination balloons. Further, each of the optical links may be referred to as a "hop" on the lightpath.

To operate as a mesh network, balloons **102**A to **102**F may employ various routing techniques and self-healing algorithms. In some embodiments, a balloon network **100** may employ adaptive or dynamic routing, where a lightpath between a source and destination balloon is determined and set-up when the connection is needed, and released at a later time. Further, when adaptive routing is used, the lightpath may be determined dynamically depending upon the current state, past state, and/or predicted state of the balloon network.

In addition, the network topology may change as the balloons **102**A to **102**F move relative to one another and/or relative to the ground. Accordingly, an example balloon network **100** may apply a mesh protocol to update the state of the network as the topology of the network changes. For example, to address the mobility of the balloons **102**A to **102**F, balloon network **100** may employ and/or adapt various techniques that are employed in mobile ad hoc networks (MANETs). Other examples are possible as well.

In some implementations, a balloon network **100** may be configured as a transparent mesh network. More specifically, in a transparent balloon network, the balloons may include components for physical switching that is entirely optical, without any electrical involved in physical routing of optical signals. Thus, in a transparent configuration with optical switching, signals travel through a multi-hop lightpath that is entirely optical.

In other implementations, the balloon network **100** may implement a free-space optical mesh network that is opaque. In an opaque configuration, some or all balloons **102**A to **102**F may implement optical-electrical-optical (OEO) switching. For example, some or all balloons may include optical cross-connects (OXCs) for OEO conversion of optical signals. Other opaque configurations are also possible. Additionally, network configurations are possible that include routing paths with both transparent and opaque sections.

In a further aspect, balloons in an example balloon network **100** may implement wavelength division multiplexing (WDM), which may help to increase link capacity. When WDM is implemented with transparent switching, physical lightpaths through the balloon network may be subject to the "wavelength continuity constraint." More specifically, because the switching in a transparent network is entirely optical, it may be necessary to assign the same wavelength for all optical links on a given lightpath.

An opaque configuration, on the other hand, may avoid the wavelength continuity constraint. In particular, balloons in an opaque balloon network may include the OEO switching systems operable for wavelength conversion. As a result, balloons can convert the wavelength of an optical signal at each hop along a lightpath. Alternatively, optical wavelength conversion could take place at only selected hops along the lightpath.

Further, various routing algorithms may be employed in an opaque configuration. For example, to determine a primary lightpath and/or one or more diverse backup lightpaths for a given connection, example balloons may apply or consider shortest-path routing techniques such as Dijkstra's algorithm and k-shortest path, and/or edge and node-diverse or disjoint routing such as Suurballe's algorithm, among others. Additionally or alternatively, techniques for maintaining a particular Quality of Service (QoS) may be employed when determining a lightpath. Other techniques are also possible.

2b) Station-Keeping Functionality

In an example embodiment, a balloon network **100** may implement station-keeping functions to help provide a desired network topology. For example, station-keeping may involve each balloon **102**A to **102**F maintaining and/or moving into a certain position relative to one or more other balloons in the network (and possibly in a certain position relative to the ground). As part of this process, each balloon **102**A to **102**F may implement station-keeping functions to determine its desired positioning within the desired topology, and if necessary, to determine how to move to the desired position.

The desired topology may vary depending upon the particular implementation. In some cases, balloons may implement station-keeping to provide a substantially uniform topology. In such cases, a given balloon **102**A to **102**F may implement station-keeping functions to position itself at substantially the same distance (or within a certain range of distances) from adjacent balloons in the balloon network **100**.

In other cases, a balloon network **100** may have a non-uniform topology. For instance, example embodiments may involve topologies where balloons area distributed more or less densely in certain areas, for various reasons. As an example, to help meet the higher bandwidth demands that are typical in urban areas, balloons may be clustered more densely over urban areas. For similar reasons, the distribution of balloons may be denser over land than over large bodies of water. Many other examples of non-uniform topologies are possible.

In a further aspect, the topology of an example balloon network may be adaptable. In particular, station-keeping functionality of example balloons may allow the balloons to adjust their respective positioning in accordance with a change in the desired topology of the network. For example, one or more balloons could move to new positions to increase or decrease the density of balloons in a given area. Other examples are possible.

In some embodiments, a balloon network **100** may employ an energy function to determine if and/or how balloons should move to provide a desired topology. In particular, the state of a given balloon and the states of some or all nearby balloons may be input to an energy function. The energy function may apply the current states of the given balloon and the nearby balloons to a desired network state (e.g., a state corresponding to the desired topology). A vector indicating a desired movement of the given balloon may then be determined by determining the gradient of the energy function. The given balloon may then determine appropriate actions to take in order to effectuate the desired movement. For example, a balloon may determine an altitude adjustment or adjustments such that winds will move the balloon in the desired manner.

2c) Control of Balloons in a Balloon Network

In some embodiments, mesh networking and/or station-keeping functions may be centralized. For example, FIG. **2** is a block diagram illustrating a balloon-network control system, according to an example embodiment. In particular, FIG. **2** shows a distributed control system, which includes a central control system **200** and a number of regional control-systems **202**A to **202**B. Such a control system may be configured to coordinate certain functionality for balloon network **204**, and as such, may be configured to control and/or coordinate certain functions for balloons **206**A to **206**I.

In the illustrated embodiment, central control system **200** may be configured to communicate with balloons **206**A to **206**I via number of regional control systems **202**A to **202**C. These regional control systems **202**A to **202**C may be configured to receive communications and/or aggregate data from balloons in the respective geographic areas that they cover, and to relay the communications and/or data to central control system **200**. Further, regional control systems **202**A to **202**C may be configured to route communications from central control system **200** to the balloons in their respective geographic areas. For instance, as shown in FIG. **2**, regional control system **202**A may relay communications and/or data between balloons **206**A to **206**C and central control system **200**, regional control system **202**B may relay communications and/or data between balloons **206**D to **206**F and central control system **200**, and regional control system **202**C may relay communications and/or data between balloons **206**G to **206**I and central control system **200**.

In order to facilitate communications between the central control system **200** and balloons **206**A to **206**I, certain balloons may be configured as downlink balloons, which are operable to communicate with regional control systems **202**A to **202**C. Accordingly, each regional control system **202**A to

202C may be configured to communicate with the downlink balloon or balloons in the respective geographic area it covers. For example, in the illustrated embodiment, balloons 206A, 206F, and 206I are configured as downlink balloons. As such, regional control systems 202A to 202C may respectively communicate with balloons 206A, 206F, and 206I via optical links 206, 208, and 210, respectively.

In the illustrated configuration, where only some of balloons 206A to 206I are configured as downlink balloons, the balloons 206A, 206F, and 206I that are configured as downlink balloons may function to relay communications from central control system 200 to other balloons in the balloon network, such as balloons 206B to 206E, 206G, and 206H. However, it should be understood that it in some implementations, it is possible that all balloons may function as downlink balloons. Further, while FIG. 2 shows multiple balloons configured as downlink balloons, it is also possible for a balloon network to include only one downlink balloon.

Note that a regional control system 202A to 202C may in fact just be particular type of ground-based station that is configured to communicate with downlink balloons (e.g. the ground-based station 112 of FIG. 1). Thus, while not shown in FIG. 2, a control system may be implemented in conjunction with other types of ground-based stations (e.g., access points, gateways, etc.).

In a centralized control arrangement, such as that shown in FIG. 2, the central control system 200 (and possibly regional control systems 202A to 202C as well) may coordinate certain mesh-networking functions for balloon network 204. For example, balloons 206A to 206I may send the central control system 200 certain state information, which the central control system 200 may utilize to determine the state of balloon network 204. The state information from a given balloon may include location data, optical-link information (e.g., the identity of other balloons with which the balloon has established an optical link, the bandwidth of the link, wavelength usage and/or availability on a link, etc.), wind data collected by the balloon, and/or other types of information. Accordingly, the central control system 200 may aggregate state information from some or all the balloons 206A to 206I in order to determine an overall state of the network.

The overall state of the network may then be used to coordinate and/or facilitate certain mesh-networking functions such as determining lightpaths for connections. For example, the central control system 200 may determine a current topology based on the aggregate state information from some or all the balloons 206A to 206I. The topology may provide a picture of the current optical links that are available in balloon network and/or the wavelength availability on the links. This topology may then be sent to some or all of the balloons so that a routing technique may be employed to select appropriate lightpaths (and possibly backup lightpaths) for communications through the balloon network 204.

In a further aspect, the central control system 200 (and possibly regional control systems 202A to 202C as well) may also coordinate certain station-keeping functions for balloon network 204. For example, the central control system 200 may input state information that is received from balloons 206A to 206I to an energy function, which may effectively compare the current topology of the network to a desired topology, and provide a vector indicating a direction of movement (if any) for each balloon, such that the balloons can move towards the desired topology. Further, the central control system 200 may use altitudinal wind data to determine respective altitude adjustments that may be initiated to achieve the movement towards the desired topology. The central control system 200 may provide and/or support other station-keeping functions as well.

FIG. 2 shows a distributed arrangement that provides centralized control, with regional control systems 202A to 202C coordinating communications between a central control system 200 and a balloon network 204. Such an arrangement may be useful to provide centralized control for a balloon network that covers a large geographic area. In some embodiments, a distributed arrangement may even support a global balloon network that provides coverage everywhere on earth. A distributed-control arrangement may be useful in other scenarios as well.

Further, it should be understood that other control-system arrangements are possible. For instance, some implementations may involve a centralized control system with additional layers (e.g., sub-region systems within the regional control systems, and so on). Alternatively, control functions may be provided by a single, centralized, control system, which communicates directly with one or more downlink balloons.

In some embodiments, control and coordination of a balloon network may be shared between a ground-based control system and a balloon network to varying degrees, depending upon the implementation. In fact, in some embodiments, there may be no ground-based control systems. In such an embodiment, all network control and coordination functions may be implemented by the balloon network itself. For example, certain balloons may be configured to provide the same or similar functions as central control system 200 and/or regional control systems 202A to 202C. Other examples are also possible.

Furthermore, control and/or coordination of a balloon network may be de-centralized. For example, each balloon may relay state information to, and receive state information from, some or all nearby balloons. Further, each balloon may relay state information that it receives from a nearby balloon to some or all nearby balloons. When all balloons do so, each balloon may be able to individually determine the state of the network. Alternatively, certain balloons may be designated to aggregate state information for a given portion of the network. These balloons may then coordinate with one another to determine the overall state of the network.

Further, in some aspects, control of a balloon network may be partially or entirely localized, such that it is not dependent on the overall state of the network. For example, individual balloons may implement station-keeping functions that only consider nearby balloons. In particular, each balloon may implement an energy function that takes into account its own state and the states of nearby balloons. The energy function may be used to maintain and/or move to a desired position with respect to the nearby balloons, without necessarily considering the desired topology of the network as a whole. However, when each balloon implements such an energy function for station-keeping, the balloon network as a whole may maintain and/or move towards the desired topology.

As an example, each balloon A may receive distance information d_1 to d_k with respect to each of its k closest neighbors. Each balloon A may treat the distance to each of the k balloons as a virtual spring with vector representing a force direction from the first nearest neighbor balloon i toward balloon A and with force magnitude proportional to d_i. The balloon A may sum each of the k vectors and the summed vector is the vector of desired movement for balloon A. Balloon A may attempt to achieve the desired movement by controlling its altitude.

Alternatively, this process could assign the force magnitude of each of these virtual forces equal to $d_I \times d_I$, wherein d_I is proportional to the distance to the second nearest neighbor balloon, for instance.

In another embodiment, a similar process could be carried out for each of the k balloons and each balloon could transmit its planned movement vector to its local neighbors. Further rounds of refinement to each balloon's planned movement vector can be made based on the corresponding planned movement vectors of its neighbors. It will be evident to those skilled in the art that other algorithms could be implemented in a balloon network in an effort to maintain a set of balloon spacings and/or a specific network capacity level over a given geographic location.

2d) Example Balloon Configuration

Various types of balloon systems may be incorporated in an example balloon network. As noted above, an example embodiment may utilize high-altitude balloons, which could typically operate in an altitude range between 17 km and 25 km. FIG. **3** shows a high-altitude balloon **300**, according to an example embodiment. As shown, the balloon **300** includes an envelope **302**, a skirt **304**, a payload **306**, and a cut-down system **308**, which is attached between the balloon **302** and payload **304**.

The envelope **302** and skirt **304** may take various forms, which may be currently well-known or yet to be developed. For instance, the envelope **302** and/or skirt **304** may be made of a highly-flexible latex material or may be made of a rubber material such as chloroprene. In one example embodiment, the envelope and/or skirt could be made of metalized Mylar or BoPet. Other materials are also possible. Further, the shape and size of the envelope **302** and skirt **304** may vary depending upon the particular implementation. Additionally, the envelope **302** may be filled with various different types of gases, such as helium and/or hydrogen. Other types of gases are possible as well.

The payload **306** of balloon **300** may include a processor **312** and on-board data storage, such as memory **314**. The memory **314** may take the form of or include a non-transitory computer-readable medium. The non-transitory computer-readable medium may have instructions stored thereon, which can be accessed and executed by the processor **312** in order to carry out the balloon functions described herein.

The payload **306** of balloon **300** may also include various other types of equipment and systems to provide a number of different functions. For example, payload **306** may include optical communication system **316**, which may transmit optical signals via an ultra-bright LED system **320**, and which may receive optical signals via an optical-communication receiver **322** (e.g., a photodiode receiver system). Further, payload **306** may include an RF communication system **318**, which may transmit and/or receive RF communications via an antenna system **340**.

The payload **306** may also include a power supply **326** to supply power to the various components of balloon **300**. The power supply **326** could include a rechargeable battery. In other embodiments, the power supply **326** may additionally or alternatively represent other means known in the art for producing power. In addition, the balloon **300** may include a solar power generation system **327**. The solar power generation system **327** may include solar panels and could be used to generate power that charges and/or is distributed by power supply **326**.

Further, payload **306** may include various types of other systems and sensors **328**. For example, payload **306** may include one or more video and/or still cameras, a GPS system, various motion sensors (e.g., accelerometers, magnetometers, gyroscopes, and/or compasses), and/or various sensors for capturing environmental data. Further, some or all of the components within payload **306** may be implemented in a radiosonde or other probe, which may be operable to measure, e.g., pressure, altitude, geographical position (latitude and longitude), temperature, relative humidity, and/or wind speed and/or wind direction, among other information.

As noted, balloon **300** includes an ultra-bright LED system **320** for free-space optical communication with other balloons. As such, optical communication system **316** may be configured to transmit a free-space optical signal by modulating the ultra-bright LED system **320**. The optical communication system **316** may be implemented with mechanical systems and/or with hardware, firmware, and/or software. Generally, the manner in which an optical communication system is implemented may vary, depending upon the particular application. The optical communication system **316** and other associated components are described in further detail below.

In a further aspect, balloon **300** may be configured for altitude control. For instance, balloon **300** may include a variable buoyancy system, which is configured to change the altitude of the balloon **300** by adjusting the volume and/or density of the gas in the balloon **300**. A variable buoyancy system may take various forms, and may generally be any system that can change the volume and/or density of gas in the envelope **302**.

In an example embodiment, a variable buoyancy system may include a bladder **310** that is located inside of envelope **302**. The bladder **310** could be an elastic chamber configured to hold liquid and/or gas. Alternatively, the bladder **310** need not be inside the envelope **302**. For instance, the bladder **310** could be a ridged bladder that could be pressurized well beyond neutral pressure. The buoyancy of the balloon **300** may therefore be adjusted by changing the density and/or volume of the gas in bladder **310**. To change the density in bladder **310**, balloon **300** may be configured with systems and/or mechanisms for heating and/or cooling the gas in bladder **310**. Further, to change the volume, balloon **300** may include pumps or other features for adding gas to and/or removing gas from bladder **310**. Additionally or alternatively, to change the volume of bladder **310**, balloon **300** may include release valves or other features that are controllable to allow gas to escape from bladder **310**. Multiple bladders **310** could be implemented within the scope of this disclosure. For instance, multiple bladders could be used to improve balloon stability.

In an example embodiment, the envelope **302** could be filled with helium, hydrogen or other lighter-than-air material. The envelope **302** could thus have an associated upward buoyancy force. In such an embodiment, air in the bladder **310** could be considered a ballast tank that may have an associated downward ballast force. In another example embodiment, the amount of air in the bladder **310** could be changed by pumping air (e.g., with an air compressor) into and out of the bladder **310**. By adjusting the amount of air in the bladder **310**, the ballast force may be controlled. In some embodiments, the ballast force may be used, in part, to counteract the buoyancy force and/or to provide altitude stability.

In another embodiment, a portion of the envelope **302** could be a first color (e.g., black) and/or a first material from the rest of envelope **302**, which may have a second color (e.g., white) and/or a second material. For instance, the first color and/or first material could be configured to absorb a relatively larger amount of solar energy than the second color and/or second material. Thus, rotating the balloon such that the first material is facing the sun may act to heat the envelope **302** as well as the gas inside the envelope **302**. In this way, the buoyancy force of the envelope **302** may increase. By rotating the balloon such that the second material is facing the sun, the temperature of gas inside the envelope **302** may decrease. Accordingly, the buoyancy force may decrease. In this manner, the buoyancy force of the balloon could be adjusted by changing the temperature/volume of gas inside the envelope **302** using solar energy. In such embodiments, it is possible that a bladder **310** may not be a necessary element of balloon **300**. Thus, various contemplated embodiments, altitude control of balloon **300** could be achieved, at least in part, by adjusting the rotation of the balloon with respect to the sun.

Further, a balloon **306** may include a navigation system (not shown). The navigation system may implement station-keeping functions to maintain position within and/or move to a position in accordance with a desired topology. In particular, the navigation system may use altitudinal wind data to determine altitudinal adjustments that result in the wind carrying the balloon in a desired direction and/or to a desired location. The altitude-control system may then make adjustments to the density of the balloon chamber in order to effectuate the determined altitudinal adjustments and cause the balloon to move laterally to the desired direction and/or to the desired location. Alternatively, the altitudinal adjustments may be computed by a ground-based or satellite-based control system and communicated to the high-altitude balloon. In other embodiments, specific balloons in a heterogeneous balloon network may be configured to compute altitudinal adjustments for other balloons and transmit the adjustment commands to those other balloons.

As shown, the balloon **300** also includes a cut-down system **308**. The cut-down system **308** may be activated to separate the payload **306** from the rest of balloon **300**. The cut-down system **308** could include at least a connector, such as a balloon cord, connecting the payload **306** to the envelope **302** and a means for severing the connector (e.g., a shearing mechanism or an explosive bolt). In an example embodiment, the balloon cord, which may be nylon, is wrapped with a nichrome wire. A current could be passed through the nichrome wire to heat it and melt the cord, cutting the payload **306** away from the envelope **302**.

The cut-down functionality may be utilized anytime the payload needs to be accessed on the ground, such as when it is time to remove balloon **300** from a balloon network, when maintenance is due on systems within payload **306**, and/or when power supply **326** needs to be recharged or replaced.

In an alternative arrangement, a balloon may not include a cut-down system. In such an arrangement, the navigation system may be operable to navigate the balloon to a landing location, in the event the balloon needs to be removed from the network and/or accessed on the ground. Further, it is possible that a balloon may be self-sustaining, such that it does not need to be accessed on the ground. In other embodiments, in-flight balloons may be serviced by specific service balloons or another type of aerostat or aircraft.

In a further aspect, balloon **300** includes a gas-flow system, which may be used for altitude control. In the illustrated example, the gas-flow system includes a high-pressure storage chamber **342**, a gas-flow tube **350**, and a pump **348**, which may be used to pump gas out of the envelope **302**, through the gas-flow tube **350**, and into the high-pressure storage chamber **342**. As such, balloon **300** may be configured to decrease its altitude by pumping gas out of envelope **302** and into high-pressure storage chamber **342**. Further, balloon **300** may be configured to move gas into the envelope and increase its altitude by opening a valve **352** at the end of gas-flow tube **350**, and allowing lighter-than-air gas from high-pressure storage chamber **342** to flow into envelope **302**.

Note that the high-pressure storage chamber in an example balloon, may high-pressure storage chamber **342** may be constructed such that its volume does not change due to, e.g., the high forces and/or torques resulting from gas that is compressed within the chamber. In an example embodiment, the high-pressure storage container **342** may be made of a material with a high tensile-strength to weight ratio, such as titanium or a composite made of spun carbon fiber and epoxy. However, high-pressure storage container **342** may be made of other materials or combinations of materials, without departing from the scope of the invention.

In a further aspect, balloon **300** may be configured to generate power from gas flow out of high-pressure storage chamber **342** and into envelope **302**. For example, a turbine (not shown) may be fitted in the path of the gas flow (e.g., at the end of gas-flow tube **350**). The turbine may be a gas turbine generator, or may take other forms. Such a turbine may generate power when gas flows from high-pressure storage chamber **342** to envelope **302**. The generated power may be immediately used to operate the balloon and/or may be used to recharge the balloon's battery.

In a further aspect, a turbine, such as a gas turbine generator, may also be configured to operate "in reverse" in order to pump gas into and pressurize the high-pressure storage chamber **342**. In such an embodiment, pump **348** may be unnecessary. However, an embodiment with a turbine could also include a pump.

In some embodiments, pump **348** may be a positive displacement pump, which is operable to pump gas out of the envelope **302** and into high-pressure storage chamber **342**. Further, a positive-displacement pump may be operable in reverse to function as a generator.

Further, in the illustrated example, the gas-flow system includes a valve **346**, which is configured to adjust the gas-flow path between envelope **302**, high-pressure storage chamber **342**, and fuel cell **344**. In particular, valve **346** may adjust the gas-flow path such that gas can flow between high-pressure storage chamber **342** and envelope **302**, and shut off the path to fuel cell **344**. Alternatively, valve **346** may shut off the path high-pressure storage chamber **342**, and create a gas-flow path such that gas can flow between fuel cell **344** and envelope **302**.

Balloon **300** may be configured to operate fuel cell **344** in order to produce power via the chemical reaction of hydrogen and oxygen to produce water, and to operate fuel cell **344** in reverse so as to create hydrogen and oxygen from water. Accordingly, to increase its altitude, balloon **300** may run fuel cell **344** in reverse so as to generate gas (e.g., hydrogen gas), which can then be moved into the envelope to increase buoyancy. Specifically, balloon may increase its altitude by running fuel cell **344** in reverse, adjusting valve **346** and valve **352** such that hydrogen gas produced by fuel cell **344** can flow from fuel cell **344**, through gas-flow tube **350**, and into envelope **302**.

To run fuel cell **344** "in reverse," balloon **300** may utilize an electrolysis mechanism in order to separate water molecules. For example, a balloon may be configured to use a photocatalytic water splitting technique to produce hydrogen and oxygen from water. Other techniques for electrolysis are also possible.

Further, balloon **300** may be configured to separate the oxygen and hydrogen produced via electrolysis. To do so, the fuel cell **344** and/or another balloon component may include an anode and cathode that attract the positively and negatively charged O- and H-ions, and separate the two gases. Once the gases are separated, the hydrogen may be directed into the envelope. Additionally or alternatively, the hydrogen and/or oxygen may be moved into the high-pressure storage chamber.

Further, to decrease its altitude, balloon **300** may use pump **348** to pump gas from envelope **302** to the fuel cell **344**, so that the hydrogen gas can be consumed in the fuel cell's chemical reaction to produce power (e.g., the chemical reaction of hydrogen and oxygen to create water). By consuming the hydrogen gas the buoyancy of the balloon may be reduced, which in turn may decrease the altitude of the balloon.

It should be understood that variations on the illustrated high-pressure storage chamber are possible. For example, the high-pressure storage chamber may take on various sizes and/or shapes, and be constructed from various materials, depending upon the implementation. Further, while high-pressure storage chamber **342** is shown as part of payload **306**, high-pressure storage chamber could also be located inside of envelope **302**. Yet further, a balloon could implement multiple high-pressure storage chambers. Other variations on the illustrated high-pressure storage chamber **342** are also possible.

It should also be understood that variations on the illustrated air-flow tube **350** are possible. Specifically, any configuration that facilitates movement of gas between the high-pressure storage chamber and the envelope is possible.

Yet further, it should be understood that a balloon and/or components thereof may vary from the illustrated balloon **300**. For example, some or all of the components of balloon **300** may be omitted. Components of balloon **300** could also be combined. Further, a balloon may include additional components in addition or in the alternative to the illustrated components of balloon **300**. Other variations are also possible.

3. Balloon Network With Optical And Rf Links Between Balloons

In some embodiments, a high-altitude-balloon network may include super-node balloons, which communicate with one another via optical links, as well as sub-node balloons, which communicate with super-node balloons via RF links. Generally, the optical links between super-node balloons may be configured to have more bandwidth than the RF links between super-node and sub-node balloons. As such, the super-node balloons may function as the backbone of the balloon network, while the sub-nodes may provide sub-networks providing access to the balloon network and/or connecting the balloon network to other networks.

FIG. **4** is a simplified block diagram illustrating a balloon network that includes super-nodes and sub-nodes, according to an example embodiment. More specifically, FIG. **4** illustrates a portion of a balloon network **400** that includes super-node balloons **410**A to **410**C (which may also be referred to as "super-nodes") and sub-node balloons **420** (which may also be referred to as "sub-nodes").

Each super-node balloon **410**A to **410**C may include a free-space optical communication system that is operable for packet-data communication with other super-node balloons. As such, super-nodes may communicate with one another over optical links. For example, in the illustrated embodiment, super-node **410**A and super-node **401**B may communicate with one another over optical link **402**, and super-node **410**A and super-node **401**C may communicate with one another over optical link **404**.

Each of the sub-node balloons **420** may include a radio-frequency (RF) communication system that is operable for packet-data communication over one or more RF air interfaces. Accordingly, each super-node balloon **410**A to **410**C may include an RF communication system that is operable to route packet data to one or more nearby sub-node balloons **420**. When a sub-node **420** receives packet data from a super-node **410**, the sub-node **420** may use its RF communication system to route the packet data to a ground-based station **430** via an RF air interface.

As noted above, the super-nodes **410**A to **410**C may be configured for both longer-range optical communication with other super-nodes and shorter-range RF communications with nearby sub-nodes **420**. For example, super-nodes **410**A to **410**C may use using high-power or ultra-bright LEDs to transmit optical signals over optical links **402**, **404**, which may extend for as much as 100 miles, or possibly more. Configured as such, the super-nodes **410**A to **410**C may be capable of optical communications at speeds of 10 to 50 GB/sec or more.

A larger number of balloons may be configured as sub-nodes, which may communicate with ground-based Internet nodes at speeds on the order of approximately 10 MB/sec. Configured as such, the sub-nodes **420** may be configured to connect the super-nodes **410** to other networks and/or to client devices.

Note that the data speeds and link distances described in the above example and elsewhere herein are provided for illustrative purposes and should not be considered limiting; other data speeds and link distances are possible.

In some embodiments, the super-nodes **410**A to **410**C may function as a core network, while the sub-nodes **420** function as one or more access networks to the core network. In such an embodiment, some or all of the sub-nodes **420** may also function as gateways to the balloon network **400**. Additionally or alternatively, some or all of ground-based stations **430** may function as gateways to the balloon network **400**.

4. Illustrative Methods

FIG. **5** is a flow chart illustrating a computer-implemented method, according to an example embodiment. Example methods, such as method **500** of FIG. **5**, may be carried out by a control system and/or by other components of balloon. A control system may take the form of program instructions stored on a non-transitory computer readable medium (e.g., memory **314** of FIG. **3**) and a processor that executes the instructions (e.g., processor **312**). However, a control system may take other forms including software, hardware, and/or firmware.

Example methods may be implemented as part of a balloon's altitude control process. Yet further, example methods may be implemented as part of or in conjunction with a balloon's power generation and/or power management processes.

4a) Altitude Control with Power Management Via Gas Flow

As shown by block **502**, method **500** involves a control system causing a balloon to operate in a first mode. While the balloon is operating in the first mode, the control system may operate the balloon's solar power system to generate power for the balloon. As the control system may cause the balloon to use at least some of the power generated by the solar power system to move gas from the envelope to the high-pressure storage chamber such that the buoyancy of the balloon decreases, as shown by block **504**. At a later point in time, the control system may cause the balloon to operate in a second mode, as shown by block **506**. While the balloon is operating in the second mode, the control system may move gas from the high-pressure storage chamber to the envelope such that the buoyancy of the balloon increases, as shown by block **508**.

In an example embodiment, the first mode may be a daytime mode and the second mode may be a nighttime mode.

Further, the balloon may include a battery in addition to the solar power system. As such, the control system may cause the balloon to operate in the first mode and use the solar power system during the daytime (e.g., when there is enough sun light for the solar power system to support some or all of the balloon's functionality), and cause the balloon to operate in the second mode and use the battery during the nighttime (e.g., when solar power may be unavailable).

In a further aspect, an example method may further involve the control system detecting a predetermined day-night transition condition, and responsively causing the balloon to transition from the daytime mode to the nighttime mode. Various day-night transition conditions are possible. For example, the control system may cause the transition at a certain time (e.g., sunset), or upon detecting that the amount of sunlight being received by the solar power system has fallen below a threshold level, among other possibilities. Other types of day-night transition conditions are also possible.

In some embodiments, the transition between modes may be an immediate switch from the daytime to nighttime mode. In other embodiments, the transition between the daytime and nighttime mode may occur over a period of time. For example, a balloon's control system may gradually increase the amount of battery power being utilized as the amount of sunlight being received, and thus the amount of power that is being generated by the solar power system decreases. Other examples are also possible.

As noted above, an example method may be implemented as part of an altitude control process. As such, altitudinal movements of the balloon may be achieved in different ways in different modes of operation. For example, in the first mode (e.g., daytime mode) the balloon may decrease its altitude by moving the gas from the envelope to the high-pressure storage chamber. More specifically, moving gas from the envelope to the high-pressure storage chamber reduces the volume in which the gas is contained and thus increases the density of the gas. Increasing the density of the gas reduces the buoyancy of the balloon and thus may cause the balloon to move to a lower altitude. Conversely, when gas is moved back into the envelope, the density of the gas decreases, which in turn may increase the buoyancy of the balloon and cause the balloon to move to a higher altitude.

In a further aspect, operation in the second (e.g., nighttime) mode may involve using the gas flow from the high-pressure storage chamber to generate power. Further, the power that is generated from the gas flow may be used to power the balloon, or may be used to charge the balloon's battery.

During the daytime, a balloon may utilize method **500** to take advantage of available solar power and store the gas that is generated when it decreases its altitude in the HP pressure, for use to increase its altitude during the night. (Note that the balloon may use other techniques to increase its altitude during the day and/or to decrease its altitude during the nighttime.) Advantageously, this altitude control process uses a renewable energy source (e.g., the sun) during the day, and may also generate power during the night (via gas flow into the envelope), when solar energy is unavailable.

4b) Altitude Control with Power Management Via Gas Flow and a Fuel Cell

In a further aspect, a balloon may use a fuel cell as part of an altitude control process and/or as part of or in conjunction with a balloon's power management process. In an example embodiment, altitude control and/or power management processes may utilize a fuel cell (or possibly multiple fuel cells) in combination with the functionality of high-pressure storage chamber described in reference to FIG. **5**. By utilizing both the fuel cell and movement of gas between the envelope and high-pressure storage chamber, a balloon may be provided with two ways of increasing buoyancy including one that generates power and one that uses power, and two ways of decreasing buoyancy including one that generates power and one that uses power.

For example, FIG. **6** is a combined operational state diagram **600** illustrating the functions of a balloon that utilizes a fuel cell and a gas-flow system for altitude control, according to an example embodiment. Operating in a manner such as that illustrated by FIG. **6** may facilitate power management via use of both the fuel cell and gas flow between the envelope and the high-pressure storage chamber for buoyancy adjustments in a manner that helps the balloon to generate and utilize power in a more efficient manner.

More specifically, a balloon may operate in a daytime mode **602** and a nighttime mode **604**. A balloon may transition between the daytime mode **602** and the nighttime mode **604**, as shown by transitions **603** and **605**.

Further, the balloon may transition between the daytime mode **602** and the nighttime mode **604** when it detects certain conditions (e.g., a certain time of day, the availability of a certain amount of sunlight (or lack thereof), etc.). Alternatively, a balloon may be instructed when to transition between the daytime mode **602** and the nighttime mode **604** by another entity, such as another balloon in the balloon network or a ground-based station, for instance.

A balloon may implement various processes that involve altitudinal adjustment, such as various types of station-keeping processes, where altitudinal movements take advantage of altitudinally varying winds to achieve longitudinal and latitudinal movement, for instance. According to an example embodiment, the daytime mode **602** and the nighttime mode **604** the may involve different techniques for increasing the balloon's altitude, and different techniques for decreasing the balloon's altitude.

In particular, while operating in the daytime mode **602**, the balloon may determine that the balloon should change its altitude, as shown by block **606** (shown within daytime mode **602**). If the balloon determines it should move to a lower altitude, the balloon may decrease its buoyancy by moving gas out of the envelope and into the high-pressure storage chamber, as shown by block **608**. To do so, the balloon may use power that is generated by its solar power system. In particular, the balloon may use power supplied by its solar power system to operate a pump, and pump gas from the envelope into the high-pressure storage chamber.

Further, if the balloon determines it should move to a higher altitude while the balloon is operating in the daytime mode **602**, then the balloon may increase its buoyancy by using its fuel cell to produce gas (e.g., hydrogen gas), and directing the gas that is produced into the envelope, as shown by block **610**. For example, the balloon may operate its fuel cell in reverse to produce hydrogen gas and oxygen gas from water. The hydrogen gas may then be moved (or allowed to move) into the balloon's envelope so as to increase buoyancy by an amount that corresponds to a desired increase in altitude. Further, in daytime mode **602**, the balloon may utilize power from its solar power system to operate its fuel cell in reverse.

Further, while operating in the nighttime mode **604**, the balloon may also determine that the balloon should change its altitude, as shown by block **606** (shown again within nighttime mode **604**). However, altitude adjustments may be accomplished differently in nighttime mode **604**. In example embodiment, if the balloon determines it should move to a lower altitude, the balloon may decrease its buoyancy by operating its fuel cell so as to use the gas from the envelope to generate power for the balloon, as shown by block **612**. For example, if the balloon uses hydrogen gas as a lifting gas, the fuel cell may cause a chemical reaction between oxygen gas and hydrogen gas from the envelope, which produces water. The chemical reaction also generates power, which may be used to power the balloon while the balloon is operating in nighttime mode **604** and/or may be used to recharge the balloon's battery.

If the balloon determines it should move to a higher altitude while the balloon is operating in the nighttime mode **604**, then the balloon may increase its buoyancy by moving gas out of the high-pressure storage chamber and into the envelope. To do so, the balloon may, for example, open a valve and allow gas that is stored in the high-pressure storage chamber to rise into the envelope. Other techniques for moving gas from the high-pressure storage chamber to the envelope are also possible.

Note that a balloon may determine that it should change altitude at various points in time, while operating in the daytime mode and/or while operating in the nighttime mode. Accordingly, block **608** and/or block **610** may each be carried out a number of times while the balloon is operating in daytime mode **602**. Similarly, block **612** and/or block **614** may each be carried out a number of times while the balloon is operating in daytime mode **602** However, it is also possible that block **608** and/or block **610** might not be carried out at all during a single period in which the balloon operates in daytime mode **602** (e.g., during a single day).

In a further aspect, note that gas could be moved between the envelope and the high-pressure storage chamber for reasons other than adjusting buoyancy and altitude control. For example, gas could be moved between the envelope and the high-pressure storage chamber as part of a pressure management process. In particular, as the envelope heats up and cools down, the pressure inside it will be much higher when the air is hot (e.g., mid-day) than when it is cold (e.g. the middle of the night). This could create a scenario where heat causes the air pressure inside the envelope to increase so much as to present a risk of popping the envelope. Accordingly, to regulate the pressure, a balloon may move some gas from the envelope to the high-pressure storage chamber. Further, the balloon could move gas back into the envelope at when it is more structurally safe to do so (e.g., after the sun sets and the temperature of the gas in the envelope decreases). Other examples are also possible.

5. Conclusion

The above detailed description describes various features and functions of the disclosed systems, devices, and methods with reference to the accompanying figures. While various aspects and embodiments have been disclosed herein, other aspects and embodiments will be apparent to those skilled in the art. The various aspects and embodiments disclosed herein are for purposes of illustration and are not intended to be limiting, with the true scope and spirit being indicated by the following claims.

What is claimed is:

1. An aerial vehicle comprising:

a solar power system configured to generate power for the aerial vehicle, wherein the aerial vehicle comprises an envelope and a high-pressure storage chamber;

a control system that is configured to cause the aerial vehicle to operate in at least a first mode and a second mode;

wherein, during operation in the first mode, the control system is configured to:

operate the solar power system to generate power;

decrease the buoyancy of the aerial vehicle by using at least some of the power generated by the solar power system to move gas from the envelope to the high-pressure storage chamber such that the buoyancy of the aerial vehicle decreases; and

increase the buoyancy of the aerial vehicle by: (a) operating a fuel cell of the aerial vehicle in reverse to produce gas, and (b) moving the gas produced by the fuel cell to the envelope;

wherein, during operation in the second mode, the control system is configured to:

decrease the buoyancy of the aerial vehicle by: (a) moving gas from the envelope to the fuel cell, and (b) operating the fuel cell so as to use the gas from the envelope to generate power; and

increase the buoyancy of the aerial vehicle by moving gas from the high-pressure storage chamber to the envelope.

2. The aerial vehicle of claim **1**, wherein the aerial vehicle is a balloon.

3. The aerial vehicle of claim **1**, wherein, during operation in the first mode, the control system is further configured to:

determine that the aerial vehicle should move in a given horizontal direction;

determine that wind at a lower altitude corresponds to the given horizontal direction; and

in response to determining that wind at the lower altitude corresponds to the given horizontal direction, use at least some of the power generated by the solar power system to move gas from the envelope to the high-pressure storage chamber such that the buoyancy of the aerial vehicle decreases.

4. The aerial vehicle of claim **1**, wherein, during operation in the first mode, the control system is further configured to:

determine that the aerial vehicle should move in a given horizontal direction;

determine that wind at a higher altitude corresponds to the given horizontal direction; and

in response to determining that wind at the higher altitude corresponds to the given horizontal direction, operate the fuel cell of the aerial vehicle in reverse and move the gas produced by the fuel cell to the envelope such that the buoyancy of the aerial vehicle increases.

5. The aerial vehicle of claim **1**, wherein, during operation in the second mode, the control system is further configured to:

determine that the aerial vehicle should move in a given horizontal direction;

determine that wind at a lower altitude corresponds to the given horizontal direction; and

in response to determining that wind at the lower altitude corresponds to the given horizontal direction, operate the fuel cell so as to use the gas from the envelope to generate power for the aerial vehicle, such that the buoyancy of the aerial vehicle decreases.

6. The aerial vehicle of claim **1**, wherein, during operation in the second mode, the control system is further configured to:

determine that the aerial vehicle should move in a given horizontal direction;

determine that wind at a higher altitude corresponds to the given horizontal direction; and

in response to determining that wind at the higher altitude corresponds to the given horizontal direction, move gas from the high-pressure storage chamber to the envelope such that the buoyancy of the aerial vehicle increases.

7. An aerial vehicle comprising:

a solar power system configured to generate power for the aerial vehicle, wherein the aerial vehicle comprises an envelope and a high-pressure storage chamber;

a control system that is configured to cause the aerial vehicle to operate in at least a first mode and a second mode;

wherein, during operation in the first mode, the control system is configured to:

operate the solar power system to generate power for the aerial vehicle;

use at least some of the power generated by the solar power system to move gas from the envelope to the high-pressure storage chamber such that the buoyancy of the aerial vehicle decreases;

determine that the aerial vehicle should move to a higher altitude and responsively: (a) operate a fuel cell of the aerial vehicle in reverse to produce gas, and (b) move the gas produced by the fuel cell to the envelope such that the buoyancy of the aerial vehicle increases; and

cause the aerial vehicle to operate in a second mode, wherein, during operation in the second mode, the control system is configured to determine that the aerial vehicle should move to a lower altitude and responsively: (a) move gas from the envelope to the fuel cell, and (b) operate the fuel cell so as to use the gas from the envelope to generate power for the aerial vehicle, such that the buoyancy of the aerial vehicle decreases.

8. The aerial vehicle of claim 7, wherein the first mode is a daytime mode and the second mode is a nighttime mode.

9. The aerial vehicle of claim 8, wherein the control system is further configured to:

detect a predetermined day-night transition condition; and

responsively cause the aerial vehicle to transition from operation in the daytime mode to operation in the nighttime mode.

10. The aerial vehicle of claim 7, wherein, during operation in the second mode, the control system is further configured to move gas from the high-pressure storage chamber to the envelope such that the buoyancy of the aerial vehicle increases.

11. The aerial vehicle of claim 7, wherein the aerial vehicle further comprises a battery, and wherein, during operation in the second mode, the control system is further configured to use power supplied by the battery.

12. The aerial vehicle of claim 7, wherein, during operation in the first mode, the control system is further configured to:

determine that the aerial vehicle should move in a given horizontal direction;

determine that wind at a lower altitude corresponds to the given horizontal direction; and

in response to determining that wind at the lower altitude corresponds to the given horizontal direction, use at least some of the power generated by the solar power system to move gas from the envelope to the high-pressure storage chamber such that the buoyancy of the aerial vehicle decreases.

13. The aerial vehicle of claim 7, wherein, during operation in the first mode, the control system is further configured to:

determine that the aerial vehicle should move in a given horizontal direction;

determine that wind at a higher altitude corresponds to the given horizontal direction; and

in response to determining that wind at the higher altitude corresponds to the given horizontal direction, operate the fuel cell of the aerial vehicle in reverse and move the gas produced by the fuel cell to the envelope such that the buoyancy of the aerial vehicle increases.

14. The aerial vehicle of claim 7, wherein, during operation in the second mode, the control system is further configured to:

determine that the aerial vehicle should move in a given horizontal direction;

determine that wind at a lower altitude corresponds to the given horizontal direction; and

in response to determining that wind at the lower altitude corresponds to the given horizontal direction, operate the fuel cell so as to use the gas from the envelope to generate power for the aerial vehicle, such that the buoyancy of the aerial vehicle decreases.

15. The aerial vehicle of claim 7, wherein, during operation in the second mode, the control system is further configured to:

determine that the aerial vehicle should move in a given horizontal direction;

determine that wind at a higher altitude corresponds to the given horizontal direction; and

in response to determining that wind at the higher altitude corresponds to the given horizontal direction, move gas from the high-pressure storage chamber to the envelope such that the buoyancy of the aerial vehicle increases.

16. A computer-implemented method comprising:

causing an aerial vehicle to operate in a first mode, wherein the aerial vehicle comprises an envelope, a fuel cell, a high-pressure storage chamber, and a solar power system;

while the aerial vehicle is operating in the first mode:

operating the solar power system to generate power for the aerial vehicle; and

at a first time, using at least some of the power generated by the solar power system to move gas from the envelope to the high-pressure storage chamber such that the buoyancy of the aerial vehicle decreases;

at a second time, determining that the aerial vehicle should move to a higher altitude and responsively: (a) operating a fuel cell of the aerial vehicle in reverse to produce gas, and (b) moving the gas produced by the fuel cell to the envelope such that the buoyancy of the aerial vehicle increases;

causing the aerial vehicle to operate in a second mode; and

at a third time, while the aerial vehicle is operating in the second mode, determining that the aerial vehicle should move to a lower altitude and responsively: (a) moving gas from the envelope to the fuel cell, and (b) operating the fuel cell so as to use the gas from the envelope to generate power for the aerial vehicle, such that the buoyancy of the aerial vehicle decreases.

17. The method of claim 16, wherein the first mode is a daytime mode and the second mode is a nighttime mode.

18. The method of claim 17, further comprising:

detecting a predetermined day-night transition condition; and

responsively causing the aerial vehicle to transition from operation in the daytime mode to operation in the nighttime mode.

19. The method of claim 16, wherein the aerial vehicle further comprises a battery, and wherein operation in the second mode further comprises using power supplied by the battery.

20. The method of claim 19, further comprising, at a fourth time, while the aerial vehicle is operating in the second mode,

moving gas from the high-pressure storage chamber to the envelope such that the buoyancy of the aerial vehicle increases.

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